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INTRODUCTION

From a purely scientific point of view, an earthquake can be considered a source of information, the acquisition of which is the subject of seismology. The information conveyed by seismic waves consists of two fundamentally different parts: The first is created during the excitation of waves at the source of the earthquake; the second is produced by the conditions of wave propagation from the source to the station, that is, by the structure of the medium. Consequently, the interpretation of seismic observations requires the solution of two fundamental problems: the determination of the velocity structure of the medium and the determination of the earthquake source parameters. Although these two problems were recognized almost simultaneously, their roles in the history of seismology are different and they developed in different ways. Until recently, the investigation of earthquake sources received much less attention than the medium, and the relevant problems were, and to a large extent remain, little investigated.

There are several reasons for this situation. One is that structural seismology provides most of our information on the conditions prevailing at great depths and is the basis for many other branches of earth science. For a long time, the results from the study of earthquake sources seemed to be of more limited interest. In the past few decades, however, the determination of source parameters has become more important, possibly being a unique source of information about the stress conditions and present motions in the earth's interior.

Another reason is that the study of earthquake sources is much more difficult than that of the earth's structure. In fact, determining the velocity structure of the medium usually requires only kinematic parameters of seismic waves (travel times for body waves and dispersion curves for surface waves), which can be obtained with relative ease from seismograms and can be accumulated from many earthquakes for joint processing, being independent of the source process. In contrast, information on the motions and conditions at an earthquake source is contained mainly in the wave dynamics (waveforms) and is unique for every earthquake. Moreover, this information is partly (and sometimes totally) lost because of distortion by instrument and propagation effects. To eliminate these effects, the earth structure must be known beforehand.

Finally, the study of earthquake sources has encountered more serious difficulties in its theoretical aspects than has the study of the earth's structure. The inversion for the earth's structure is based on the theory of elasticity, the fundamental principles of which were formulated in the nineteenth century, and the corresponding mathematical methods were developed mainly in the nineteenth and early twentieth centuries. Of course, the refinement of numerical methods and especially the computer revolution have had a great impact on interpretation techniques, but this progress has taken place within the framework of classical concepts and has barely permitted broader application of classical results. Remember that the Herglotz–Wiechert formula was obtained in 1907 and Lamb's problem was solved in 1904. On the other hand, the attempt to achieve a theoretical understanding of earthquake source phenomena led to problems that in 1907 were impossible not only to solve but even to formulate precisely owing to the absence of adequate physical concepts for such phenomena. In fact, although the concept that earthquakes are the result of fracture of the earth's material due to tectonic stress, known as the elastic rebound theory, was formulated by Reid in 1910, the basis for analyzing this phenomenon – that is, fracture mechanics (sometimes called crack mechanics) – was not initiated by Griffith until 1921 and started developing vigorously only after the Second World War. Most of the dynamic problems in fracture mechanics proved to be unsolvable analytically, at least in closed form, by means of classical methods. Consequently, it was necessary to invent specific methods of solution for practically every problem. Nonetheless, fracture mechanics introduced certain physical concepts and methods of analysis that formed a framework in which to consider the phenomena of fracture nucleation, propagation and arrest in solid bodies and, particularly, at the earthquake source.

Naturally, destructive earthquakes forced seismologists to seek better insight into the earthquake process and to begin investigating earthquake sources with the limited resources available at the time, the lack of theory being compensated for by more or less explicit intuitive hypotheses as well as by arbitrary (and sometimes contradictory) simplifying assumptions.

Investigations of earthquake sources were shaped by the work of Reid, who formulated the theory of elastic rebound based on his study of the effects of the 1906 California earthquake. In the 1920s the regularity of the distribution of the signs of first arrival of seismic waves was discovered mainly by Japanese seismologists, and the concept of nodal planes was introduced. In his paper "Notes on the Nature of Forces Which Give Rise to Earthquake Motions," Nakano (1923) formulated the problem of finding the point source in the elastic medium for which the distribution of signs of first arrivals coincides with those observed for an earthquake and derived expressions for some dipole sources using the formulas or displacements due to a point force. This idea proved to be fruitful. It can be said that Nakano's paper initiated the quantitative study of earthquake sources. For a long time thereafter, effort was directed toward the development of this body-force equivalent.

It is clear that the determination of the body-force equivalent comprises, at best, only half of the problem, since it is also necessary to relate the characteristics of this equivalent to some physical concepts of the real earthquake source, namely, to the concepts involved in Reid's elastic rebound theory. This is reflected in the term "fault-plane solution," which denotes the body-force equivalent. Somewhat imprecise considerations regarding this problem led to a situation in which two contradictory point source models, namely, single couple and double couple, were proposed on the basis of the same physical (dislocation) model. This stage in the development of earthquake source investigations is well documented by the proceedings of two international symposia on earthquake source mechanisms. The first was held in Toronto in 1957 (The Mechanics of Faulting, with Special Reference to the Fault-Plane Work; see Hodgson, 1959) and the second in Helsinki in 1960 (A Symposium on Earthquake Mechanism; see Hodgson, 1960).

This dramatic situation was well described by Hodgson (1960) in his introduction to the proceedings of the second symposium: "At the time of the previous symposium the outstanding problem was that of selecting the appropriate mechanism and, since the theory had been established, this seemed to be simply a matter of further careful observations. Since that time much more theoretical work has been done, which has complicated rather than clarified the problem, and the observational results show little consistency" (p. 301).

Both of these point models explain the presence of nodal planes for longitudinal waves, one of which coincides with the fault plane at the source. However, whereas the radiation pattern due to a double couple is symmetric with respect to nodal planes, the single couple does not have such symmetry. This lack of symmetry would permit, if the single-couple model were correct, the determination of the actual fault plane from the signs of the S-wave arrivals. The impossibility of determining the actual fault plane in the framework of the double-couple model made an alternative interpretation of the axes of the point source orientation desirable. The conventional labels for these axes, P, T, and B, where P denotes pressure and T tension, were introduced to indicate that the axes coincide with the principal axes of the initial stress tensor causing the earthquake. Actually, these axes are the principal axes of the moment tensor of the equivalent point source. They characterize the distribution of fictitious body forces that would generate, in the medium without discontinuity, the same elastic field that is actually produced by the dislocation (fracture) at the source. Nevertheless, this interpretation is not entirely meaningless. In fact, assuming that the fault plane coincides with the plane of maximum shear stress, these axes would coincide with the principal axes of the stress tensor. This assumption, however, is not plausible from the physical point of view. For example, in the framework of the Coulomb–Mohr theory of strength, the fault plane would not coincide with the plane of maximum shear stress. Besides, when slip occurs along a preexisting fault, the plane of maximum shear stress (even if it initially coincided with the fault plane) may deviate from the fault plane on geologic time scales. Perhaps because of these considerations, this interpretation has not been widely adopted.

Discussion of the equivalent point source model concluded with the acceptance of the dislocation model. Later, by means of the dynamic Green functions, the double-couple model was related to the final slip distribution on the fault due to an earthquake. With these Green functions, it is possible to obtain an expression for the components of an elastic field at any point in terms of the displacement jump (the Burgers vector) distribution and history on the fault. The simplicity of this representation led to the development of a large variety of source models. The common feature of these models was that the distribution of the displacement jump on the fault surface was assumed arbitrarily (and in most cases as constant), and it was not clear to what extent the results depended on the choice of a particular distribution. This remark also applies to static dislocation models with a constant Burgers vector, which were proposed to describe the residual displacement at the earth's surface due to earthquakes. Essentially, such models represent a transfer to seismology of the theory of dislocations in an elastic medium – the so-called continuum theory of dislocations – developed to describe the behavior of dislocations in crystals. However, if, for dislocations in crystals, the constancy of the Burgers vector is due to the discreteness of the lattice structure, then for macrodislocation, which is what the earthquake source is, the assumption of the constancy of the Burgers vector, that is, a Volterra dislocation, is groundless and was accepted for the sake of simplicity. As Chinnery (1969) wrote:

> The theory . . . specifies in effect the displacement over a fault plane. As we have seen, it may be more useful physically to specify the stress acting across the face of a fault, and some improvements in the basic theory are needed to adequately include the effect of friction on the fault plane.
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> However, in the present author's opinion, there is a definite limit to the amount of complexity that should be included in models designed for the study of faulting. The reason for this, as we have mentioned, is the general lack of adequate field data. The usefulness of any theory must be judged on its ability to predict new results, which may then be compared with observation. At the present time field data do not have the resolution to be able to distinguish between different theories which involve large numbers of variables. The complexity of the geology in the neighborhood of most active faults suggests that it may be a long time before there is a significant improvement in this situation.

Chinnery, here, is quite certain that the crack model for an earthquake fault has a stronger physical basis than the dislocational model with a constant Burgers vector. His only justification for the latter model is the insufficient accuracy of observations, which does not permit one to choose between the cracks-with-friction model and the Volterra dislocation model. It is true that geophysical observations, as such, are not likely to become sufficiently definite in the near future to permit a choice to be made between theoretical models. However, Chinnery's conclusion, that in that case any one of the observationally indistinguishable models is acceptable, does not follow.

To describe the fracture at an earthquake source as a crack, it is necessary to know the initial distribution of stress on the fracture surface before the earthquake and the laws governing the fracture propagation and interaction of the fault faces. Then, the distribution of the displacement jump on the fault becomes one of the unknowns. When this distribution is found, solving for other quantities reduces to the use of Green's formula, as in the above-mentioned dislocation models. Thus, the difference between modeling faults as cracks and as dislocations with a variable Burgers vector (Somigliana dislocation) is not as drastic as it may seem. When describing faults as fractures, one assumes some physical laws governing the fracturing and the external action applied to the fault (initial stress), and the motion along the fracture and within the surrounding medium is solved for, whereas in dislocational models, the motion along the fault is assumed. This is analogous to the two ways of describing the motion of a material point: kinematic when its trajectory is given, and dynamic when the forces acting on this point and the laws governing its motion are given but the trajectory is unknown. In the case of fracture, when it is described as a dislocation (displacement jump as a function of space and time is given, i.e., the trajectories of relative motion of all the initially adjacent particles), we will call it kinematic description, and when it is described as a crack, we will call it dynamic.[1] This terminology stresses the fact that both descriptions are related to the same thing, that is, fracture. At the same time, this discussion implies that the kinematics of fractures is an insufficient basis for the theory of earthquake sources because the displacement jump across the fault cannot be related to the physical laws governing the nucleation and propagation of fractures in a continuous medium and to the physical conditions that produce a particular fracture.

Since the 1960s, the dynamic description of the source has been generally accepted. With this description some new fundamental parameters of the source have been introduced into seismology. These parameters, such as stress drop, average slip, and fracture area, have replaced ones like source volume and strain release, which could not be formalized within the framework of the crack (fracture) model of the source. The notions that led to the introduction of parameters such as source volume were partly contained in the classic work of Reid (1910), as was the concept of the source as a fracture. A theory founded on these notions was developed by Benioff (1951). It is based on the assumption

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[1] The term "dynamic" has two meanings: as the opposite either of "kinematic" or of "static." It is used here in the first sense, which leads to expressions such as "static problems for dynamically described fracture."

that fracture at an earthquake source occurs when the stress in a volume reaches the rock strength, the material breaks within the whole volume (the source volume), and the accumulated elastic energy in this volume is released. This energy was assumed to coincide with the seismic energy. Energy is released when elastic strain is transformed (totally or partially) into nonelastic strain as a result of the fracture. Since the elastic strain energy density is equal to the product of rigidity times the square of strain (for shear strain), the magnitude of the strain release, which is proportional to the square root of the seismic energy, can be evaluated. Benioff (1955) applied these considerations to the aftershock sequence of the 1952 Kern County, California, earthquake, which at the time was more extensively recorded than any previous aftershock sequence. This was the first instance in which portable and sensitive seismographs were set up on such a large scale within a few hours after the main shock in an earthquake area with good azimuthal distribution around the epicentral area. Benioff assumed that the source volume of the aftershocks coincided with the source volume of the main shock. Then the sum of the square roots of energies of aftershocks was proportional to the accumulated strain release, permitting the study of the dependence of strain release on time (Benioff plot). Identifying the strain release thus obtained with nonelastic strain within the source volume, Benioff considered the rheological properties of this volume and suggested an explanation for the very existence of aftershocks as well as for the time dependence of their magnitudes.

The mathematical simplicity and seemingly obvious physical basis of this theory make it appealing, so it is not surprising that it was readily accepted by practical seismologists. Benioff plots, not only for aftershock sequences, but for all earthquakes in seismically active zones and even the whole earth, were found to be a convenient means of analyzing time variations in seismicity. But it soon became clear that this theory could not be accepted without reservation. Even if one agrees that the fracture at the source occurs throughout a volume, the elastic strain energy must drop in the medium surrounding this volume as well, and consequently not only that volume in which fractures occur but the entire volume in which elastic strain energy is released should be considered to be the source volume. An attempt to modify Benioff's theory was made by Bullen (1953), who identified the source volume with the volume in which the stress was near the strength limit before the earthquake. Later, Bullen (1963, Chap. 15) extended this volume, considering the source volume to be that region where the major part of the energy released

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during the earthquake was accumulated. Actually he assumed that all of the elastic strain energy released during an earthquake was confined to a finite volume surrounding the source and that this volume was not larger by more than one order than the fracture region at the source.

At the same time, Tsuboi was considering similar ideas, but with a difference. In Benioff's theory, the energy of an earthquake is determined by the earthquake volume, so that a larger earthquake corresponds to a higher stress and a smaller one to a lower stress. Tsuboi (1956) suggested that the stresses for larger and smaller earthquakes are the same but that the volume differs and hence that larger earthquakes correspond to larger source volumes than smaller ones.

Benioff, Bullen, and Tsuboi all proceeded on the assumption that an earthquake leads to total release of the elastic energy accumulated in the source volume – that is, to total stress release in the volume. However, since the total energy release during an earthquake is simply related to the fracture area and the stress drop at the source, there is no need for any notion of source volume, and the concepts of source volume and strain release must be replaced by those of fracture area and stress drop.

In the early 1960s it started to become clear that the investigation of earthquake sources needed a more solid basis, namely, the physics of fracture in solid bodies. By this time the mechanics of brittle fracture, which is concerned with the development of fractures in solids, was fairly advanced and seemed to be a proper foundation for earthquake source theory. However, a simple transfer of the results obtained in fracture mechanics to seismology was impossible. The mechanics of brittle fracture was developed for engineering applications. In engineering, one is interested not in the process of fracture but in its prevention. Accordingly, in fracture mechanics attention was paid mainly to the theory of the critical (equilibrium) state of solids containing cracks. As for the dynamics of fracture – that of the fracture propagation process – very few experimental data were available and only the simplest problems had been solved. Moreover, under usual service conditions, the material is fractured, in most cases, in tensile mode, and fracture mechanics was concerned mainly with tensile cracks. For seismological applications, it was necessary to develop the theory of dynamic fracture propagation especially for shear fracture. Thus, there arose a need to generalize brittle fracture mechanics and to develop a method of solving dynamic problems of shear fracture propagation. The transfer of fracture mechanics to seismology required the reexplication of many mechanical terms.

In geophysics as a whole, forward problems are of minor interest, serving only to elucidate underlying physical phenomena. More important are inverse problems – problems that require the distribution of material parameters and motions in the earth's interior to be determined from surface observations. The inverse problem for the earthquake source has been formulated as one of reconstructing the displacement jump distribution and history over the fault surface at the source. The solvability of this problem was investigated, and two conclusions were reached: (1) Motion at the source is uniquely determined from its far-field seismic radiation (uniqueness theorem); (2) it is possible to construct a displacement jump distribution confined to an arbitrarily small area that produces seismic far-field radiation arbitrarily close to the observed one (instability theorem). These features, common to most inverse problems, imply that this problem cannot be solved without a priori information, in addition to seismic observations.

Chinnery's opinion, that the scarceness of observational data prevents one from distinguishing among sufficiently complex models of the source, has already been cited. Aki (1972a) writes: "Since the slip motion is a function of time and two space coordinates, a complete inversion is extremely difficult. The only practical inversion method is to describe the kinematics of rupture growth in a fault plane using a small number of parameters, and then determine those parameters from the seismograms." At first glance, these opinions are supported by the instability theorem. However, this theorem implies that, in principle, it is possible to construct two models with a finite number of parameters having arbitrarily different values, indistinguishable from one another with arbitrarily accurate seismic observations. Therefore, the additional constraints that have to be introduced for the practical solution of the inverse problem cannot be arbitrary, but they should follow from the physics of the source process. The latter is most adequately described within the framework of fracture mechanics.

Independent of this conceptual development, progress was made in practical seismology, which can be considered an approach to the solution of the inverse problem just described. The asymmetric Rayleigh wave radiation pattern from the 1952 Kern County, California, earthquake (Gutenberg, 1955) initiated the idea that the fracture speed was about the Rayleigh or shear wave speed of the medium. A similar fracture speed was found from surface waves of the great Chilean earthquake (Ben-Menahem and Toksöz, 1963). This led to the commonly accepted assumption that the size of the fracture area at the source is related to the pulse duration by the factor of Rayleigh or shear wave velocity. In 1966, Aki developed a method of determining the seismic moment and connected it with average slip and the area of fracture at

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the earthquake source. Then, from the seismic moment and fault size, the stress drop could be estimated. This development provided a unique possibility for estimating the stress conditions in the earth's interior. Nowadays, the determination of the seismic moment, stress drop, and so on has become routine, and together with fault-plane solutions comprises a firm support for global tectonic conclusions. In a sense, however, these developments went too far. Some nonphysical quantities, such as effective stress and seismic efficiency, were introduced and used broadly for drawing geophysical conclusions. The formalistic application of spectral techniques of seismic moment determination of small earthquakes became commonplace and produced a great amount of meaningless and misleading data. Sometimes, there was discussion of empirical relations between essentially identical quantities that differed only in notation and constant factors. (Some limitations of the applicability of these concepts and methods are discussed in Chapter 4 of this book.) Nevertheless, the impact of this progress on the development of earthquake seismology and its relation to other branches of geoscience cannot be overestimated.

In general, to obtain a complete description of the earthquake source it is necessary to determine the slip and stress fields on the propagating fault in space and time. Investigation of the properties of the inverse problem showed that this would be difficult, if not impossible. Instead, one can determine some overall features of the source – for example, the stress drop or slip averaged over the fault or the seismic moment tensor. If the principal axes of the source moment tensor do not change during an earthquake – that is, if the direction of faulting and the direction of slip on the fault do not change – then the time history of the moment tensor can be split into the (static) seismic moment tensor and a function describing its time dependence. This function is called the source time function. Since 1981 seismic moment tensors have been determined routinely and are now reported by Dziewonski and co-workers in the *Physics of the Earth and Planetary Interiors* as well as by the U.S. Geological Survey in its monthly listings in *Preliminary Determination of Epicenters*. The International Seismological Centre also plans to include these solutions in its monthly bulletins in the near future. Fault-plane solutions are now inferred not only from the signs of first arrivals, but also from the principal axes of the seismic moment tensor. Occasionally, differences are observed between these solutions. Such differences can sometimes be interpreted as having physical meaning; for example, the fault plane may have changed direction during propagation. Source time functions are now also a commonly determined quantity. The articles of